

PROGRESS REPORT OF FY 2000 ACTIVITIES: CONTINUED DEVELOPMENT OF AN INTEGRATED SOUNDING SYSTEM IN SUPPORT OF THE DOE/ARM EXPERIMENTAL PROGRAM (Interagency Agreement No. DE-AI03-94ER61742)

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SCIENTIFIC GOALS OF RESEARCH

The basic goals of the research are to develop and test algorithms and deploy instruments that improve measurements of atmospheric quantities relevant to radiative transfer and climate research. Primary among these atmospheric variables are integrated amounts of water vapor and cloud liquid, as well as profiles of temperature, water vapor and cloud liquid. A primary thrust of this research is to combine data from instruments available to ARM to maximize their importance in radiative transfer and climate research. To gather data relevant to these studies, participation in field experiments, especially intensive operating periods, as well as the subsequent analysis and dissemination of collected data, is of primary importance. Examples of relevant experiments include several Water Vapor Intensive Operating Periods at the Southern Great Plains Cloud And Radiation Testbed site, experiments in the Tropical Western Pacific such as PROBE and Nauru'99, and experiments at the North Slope of Alaska/Adjacent Arctic Ocean site.

ACCOMPLISHMENTS

- Joint Participation with NASA Goddard Space Flight Center in the Arctic Winter Radiometric Experiment held at the NSA/AAO site near Barrow, Alaska, in March 1999. Significant results include the first time operation of 30 microwave, millimeter and sub-millimeter radiometric channels, the correction of the ARM Microwave Radiometer (MWR) to derive accurate measurements in an extreme environment, and the comparison of contemporary absorption models in modeling downwelling radiance.
- Participation in the Nauru'99 experiment primarily through the analysis of ARM MWR and radiosonde data. First, it was shown that the MWR was in excellent calibration by two independent methods. Next, the necessity of a correction algorithm for ARCS2 radiosonde data was shown using the MWR data, and finally the Vaisala radiosonde correction algorithm was evaluated, using the MWR data as comparison. Data from the R/V Ron H. Brown and the MIRAI were also used in the radiosonde evaluations.
- A special session devoted to the Atmospheric Radiation Measurement Program was organized at the July 2000 meeting of the International Geoscience and Remote Sensing Society (IGARSS'2000) and several prominent ARM scientists were included as invited speakers.

PROGRESS AND ACCOMPLISHMENTS DURING LAST TWELVE MONTHS

(1). THE NSA/AO ARCTIC WINTER RADIOMETRIC EXPERIMENT

The Millimeter-wave Radiometric (MMWR)-Arctic experiment was conducted in March 1999 at the North Slope of Alaska/Adjacent Arctic Ocean Cloud and Radiation Testbed (NSA/AO CART) site. During the experiment, the NASA Goddard Space Flight Center and the NOAA Environmental Technology Laboratory (ETL) deployed four microwave radiometer systems with a total of 24 radiometric channels ranging in frequency from 20.6 GHz to 340 GHz. One of the objectives of this experiment was to evaluate, during extreme cold conditions, the performance of the ARM dual-channel (23.8 and 31.4 GHz) microwave radiometer (MWR) that is routinely operated at the CART site to derive precipitable water vapor (PWV) and cloud liquid water. The MWR measurements are compared with water vapor measurements using frequency channels around the much stronger 183 GHz water vapor absorption line. NASA's Millimeter-wave Imaging Radiometer (MIR) has three channels near the 183 GHz absorption line and ETL's Circularly Scanning Radiometer (CSR) has seven channels around 183 GHz. In our analysis, we focused on the evaluation of the performance of the ARM MWR by comparing its PWV retrievals with those derived from the 183 GHz channels and radiosondes, which were released at the NSA/AO CART site.

CALIBRATION METHODS

The MIR and CSR systems both had two external blackbody reference targets, one at the ambient temperature of about -30 C and the other at 26 C. During each scan, the radiometers observed each of the reference targets once and the voltage measurements of the atmospheric portion of the scan were linearly interpolated or extrapolated using these two reference points. For channels with low atmospheric opacity, the measurements were also calibrated by the tipping-curve calibration procedure (Han and Westwater 2000) in which a calibration factor in the radiometer equation is adjusted to yield a straight line of opacity τ vs. airmass a that passes through the origin.

INTER-COMPARISONS OF BRIGHTNESS TEMPERATURE AND PRECIPITABLE WATER VAPOR MEASUREMENTS

The CSR 183 channels were calibrated first using blackbody reference targets and then re-calibrated using the tipcal method because of a problem in the hot reference load. The MIR 183 channels were calibrated with blackbody references whose characteristics had been carefully evaluated in laboratory tests. The recently constructed CSR did not have the advantage of such testing. Both of the radiometers performed continuous elevation scans, but due to instrument differences, the scan patterns were different, the principal difference being that the CSR performed a symmetrical scan that yielded good data over roughly three air masses. The two MWR channels were initially calibrated and then re-calibrated, using different tipcal averaging methods. As shown in Figs. 1 and 2, the two 183 GHz radiometer systems agreed very well, especially the 183.31 +/- 7 channels, which are used to derive PWV in this study.

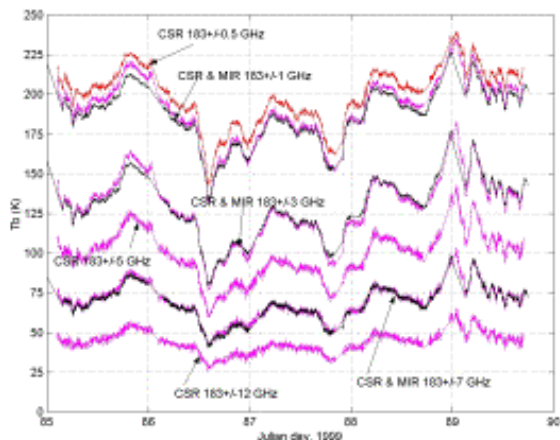


Fig. 1. Time Series of T_b around 183 GHz. Red-CSR; Black-MIR. PI's: Y. Han and E. Westwater, CIRES, Univ. of Colo./NOAA, 2000.

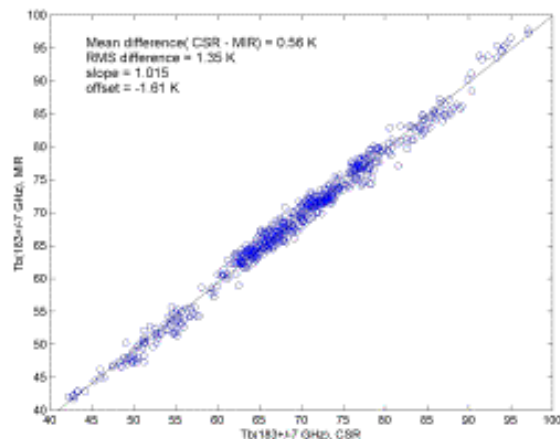


Fig. 2. Statistics of comparisons between CSR and MIR 183.31 \pm 7 channels. NSA/AAO March 7-30, 1999. PI's: Y. Han and E. Westwater.

However, initial comparisons of the 183 GHz with the original archived ARM MWR brightness temperature T_b measurements showed substantial differences. These differences were the result of a software attempt to compensate for improper temperature regulation at low temperatures. These data were re-calibrated by ETL using an instantaneous calibration factor. Fig. 3 shows Precipitable Water Vapor (PWV) derived from original and ETL-corrected ARM MWR data. As shown in Fig. 4, the corrected ARM MWR data, when converted to is in excellent agreement with both MIR and CSR radiometer data. Comparisons with NWS radiosondes are about two tenths of mm wetter than both of the radiometric measurements.

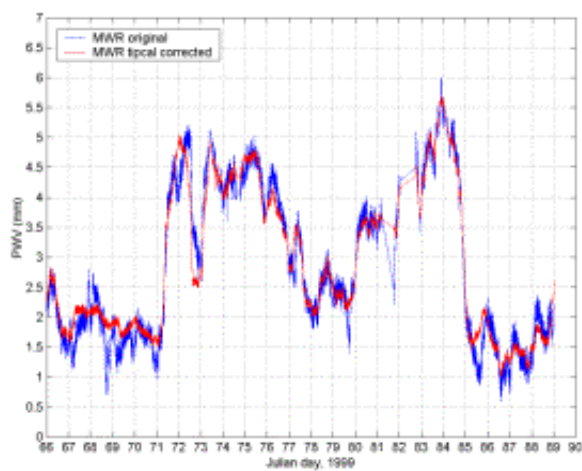


Fig. 3. Time series of PWV obtained from ARM original and re-calibrated data. NSA/AAO. PI's: Y. Han and E. Westwater, CIRES, 2000.

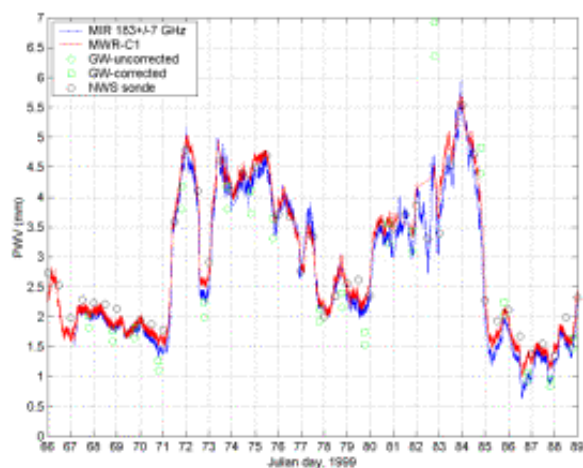


Fig. 4. Time series of MIR (blue) and CSR (red). NSA/AAO. PI's: Y. Han and E. Westwater.

CONCLUSIONS AND PLANS

The use of the instantaneous tip cal method dramatically improved ARM MWR retrievals, but it is still an open scientific question whether a 183 GHz radiometer is needed to improve PWV retrievals at concentrations from 0.8 to 3.0 mm. One stumbling block was the lack of radiosondes at the NSA/AAO site. In the future, we would like to repeat the experiment, but with a minimum of 4, and perhaps as many as 6 launches a day.

(2). MICROWAVE RADIOMETERS AND RADIOSONDES DURING NAURU'99

Previous experience, both in the PROBE experiment in the Tropical Western Pacific and during Water Vapor Intensive Operating Periods (WVIOPs) at the ARM Southern Great Plains CART site, indicated the need for adjustments to Vaisala Humicap RS80 humidity soundings. The need for such corrections has been identified by measurements of water vapor by microwave radiometers and the subsequent adjustments by scaling of water vapor profiles. During Nauru99, a variety of ground- and ship-based instruments were available to test the quality of radiosonde (RAOB) soundings in the tropical environment around the island of Nauru. In particular, nearly simultaneous RAOB soundings from the Atmospheric Radiation and Cloud Station (ARCS-2) and from the R/V Ronald H. Brown (RHB) were available. In contrast to the earlier PROBE experiment, the lot numbers of the Vaisala RAOBs were available for subsequent analysis. A variety of remote sensing and *in situ* measurements were also available. These instruments at ARCS-2 include the Radiometrics Microwave Radiometer (MWR) and a Vaisala ceilometer. Of special interest to our analysis was our independent calibration of the MWR that used a blackbody calibration target cooled by Liquid Nitrogen (LN₂). The RHB arrived at Nauru on July 5 and assumed a stationary position close to the ARCS-2 location approximately 1 km away. The first indication that there were substantial differences between ARCS-2 and RHB radiosondes was observed on the very first day that the ship was in close proximity to the island. Fig. 5 shows a time series of brightness temperatures (T_b) observed by the MWR at 23.8 and 31.4 GHz, and T_bs calculated from various radiosonde profiles. The T_b model used in these calculations was the latest Rosenkranz (1998) absorption model. Somewhat surprisingly, the RAOB data from the RHB agreed much better with the MWR than those from the co-located ARCS-2 soundings. The triangles show data that were calculated from corrected ARCS-2 soundings using a procedure described by Lesht (1999).

The results of Fig. 5 showed that, at the very least, there were significant differences between RAOBs that were launched at nearly the same time from the RHB and from the ARCS-2. A change in experimental plan was made and for five soundings, RAOB packages from the two sites were interchanged. This time, the original RHB radiosondes were in close agreement with the MWR, while the original ARCS-2 RAOBS, now launched from the RHB, were in substantial disagreement with the MWR. Thus, when the RAOBs were exchanged, the results were consistent with a RAOB problem, not a site problem. Again, using the procedure of Lesht (1999), the corrected RAOBs were in good agreement with the MWR T_bs. The reasons for the problem are now known to be associated with contamination of the RS80 humidity element as it ages. Later on in this report, we present results evaluating the accuracy of the RAOBS and their correction, as a function of RAOB age.

Many of our comparisons rely on the accuracy and consistency of the ARCS-2 MWR. During this experiment, the radiometer was run in a nearly continuous tip cal mode. When the sky conditions were favorable, as determined by symmetry of radiometry scans, the radiometer continued scanning at angles corresponding to the air masses 1, 1.5, 2.0, and 2.5 (elevation angles of 90, 41.8, 30, and 23.6 degrees). When clouds were present, angular symmetry was destroyed, and the radiometer went into a zenith-observing mode. Since, we can not calculate brightness temperatures from RAOBs during cloudy conditions, we will focus on clear conditions only; another reason for focusing on clear conditions is that during these conditions, calibration can be done on a nearly continuous basis. The original ARM calibration algorithm was used on the data and excellent data were obtained. We applied the ETL calibration method (Han and Westwater, 2000) to the same tip cal data, and nearly identical results were obtained. Our results, requiring beam width and angular-dependent mean radiating temperatures, use equivalent zenith brightness temperatures as a measure of calibration quality. Rms departures of this measure were frequently better than 0.2 K, indicating a high degree of atmospheric stratification and antenna beam symmetry. We also performed a LN2 calibration experiment, in which a blackbody reference target (or load) was filled with LN2 and placed over the MWR. The measured Tbs during this experiment are shown in Fig. 6. For the first two minutes after the load was inserted, the measured Tbs were about 79.6 K which is close to the expected value of 79.4 ± 1.9 K (F. Solheim, private communication). After the first two minutes, moisture condensed on the underside of the Styrofoam container and increasingly spurious observations were obtained. However, the few minutes of good measurements indicated that the MWR was accurate to within ± 1 K. This single target calibration measurement, together with the continuous high quality of tip cals, indicated that the MWR could be used as a comparison standard for the experiment.

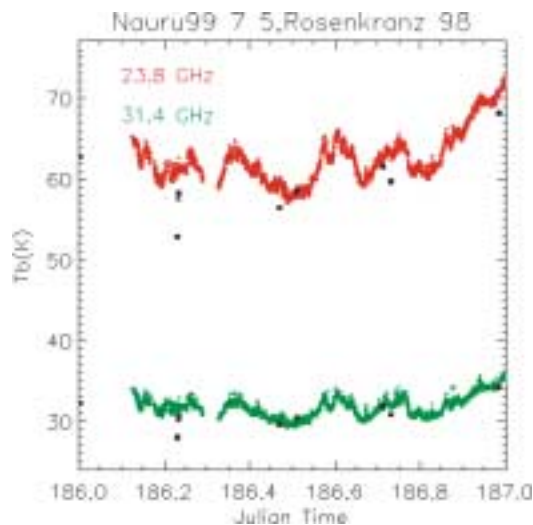


Fig. 5. Time series of MWR Tb during July 5, 1999. ■ - calculated from original ARCS2, RAOBS ► - calculated from corrected ARCS2 RAOBS, # - calculated from Ron. H. Brown RAOBS. Absorption model: Rosenkranz (1998). PI: E. R. Westwater, CIRES/Univ. of. Colo./NOAA-ETL, 2000.

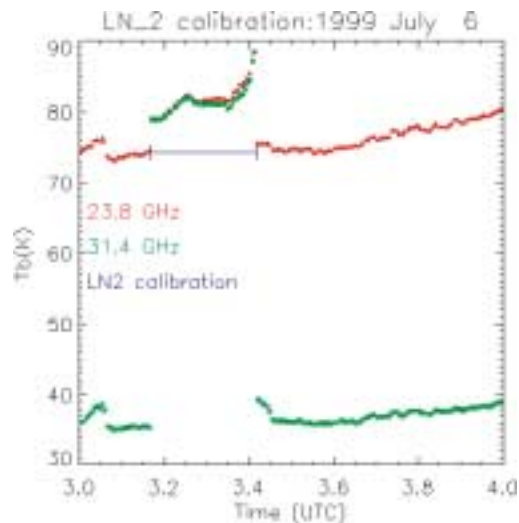


Fig. 6. Results of the LN2 calibration during Nauru'99, July 6, 1999. PI: E. R. Westwater, CIRES/Univ. of Colo./NOAA-ETL, 2000.

The manufacturers of Vaisala radiosondes have developed a proprietary algorithm to correct for the dry bias problem (Lesht, 1999). We have used a version of the algorithm that makes the correction based only on the age of the RAOB. Since we were also worried about diurnal effects, we divided our data samples into day and night subsets, and for these subsets compared Tbs measured by the ARM MWR with calculations, based on the Rosenkranz (1998) absorption model for both the original and corrected radiosondes. Our analysis showed that no statistically significant effects were present. Fig. 7 shows a scatterplot showing the comparison of corrected and uncorrected Tb calculations vs. the MWR Tbs for the period of June 15 to July 15, 1999. Since the performance of the algorithm as a function of RAOB age was an important issue, we plotted the differences between measurements and calculations as a function of RAOB age. The results, shown for ARCS-2 in Fig. 8, were surprising, and showed that although the algorithm, in general, improved the results, the improvement did not always occur for all RAOB lots. In fact, for the RAOB lots corresponding to the age around 360 days, the correction worsened the results.

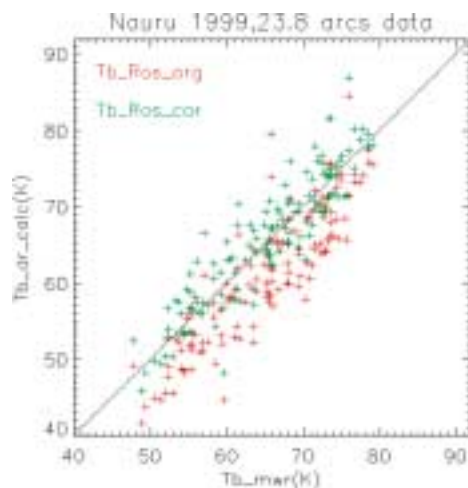


Fig. 7. Comparison of Tb calculated from original (red) and corrected (green) RAOBs vs. ARM MWR data at 23.8 GHz. Nauru'99, June 15-July 15, 1999. Absorption model - Rosenkranz (1998). PI: E. R. Westwater, CIRES, Univ. of Colo./NOAA-ETL, 2000.

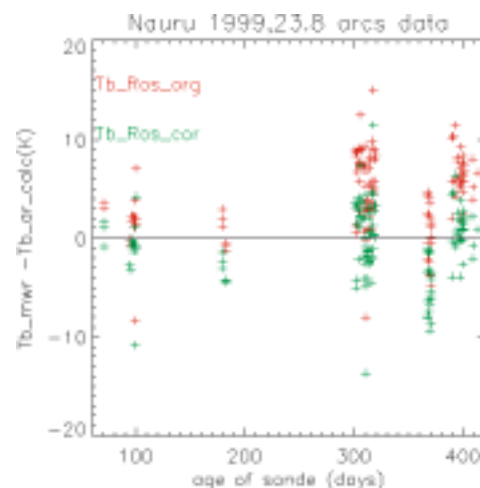


Fig. 8. Difference between measured and calculated Tbs from original (red) and corrected (green) RAOBs. Absorption model: Rosenkranz (1998). Nauru'99, June 15-July 15, 1999. PI: E. R. Westwater, CIRES, Univ. of Colo./NOAA-ETL, 2000.

CONCLUSIONS, DISCUSSION, AND PLANS

The ARM MWR operating at the ARCS-2 provided an excellent data set for the entire Nauru-99 experiment. The calibration accuracy was verified by a LN2 blackbody target experiment and by consistent high-quality tip calcs throughout the experiment. The data thus provide an excellent baseline for evaluation of the quality and consistency of Vaisala RAOBs that were launched from ARCS-2. Our preliminary results indicate that substantial errors, sometimes of the order of 20 % in PWV, occurred with the uncorrected RAOBs. When the Vaisala correction algorithm was applied to the RAOBs, better agreement with the MWR was

obtained. However, the improvement was noticeably different for different RAOB lots and was not a monotonic function of RAOB age.

We have also performed our brightness temperature calculations with two other absorption algorithms - Liebe 87 and Liebe 93. The Liebe 87 model was in close agreement with Rosenkranz 98, but neither was in agreement with Liebe 93. One task in completing this study will be to use scaled RAOB data using all of the models to calculate infrared radiance and then to compare these calculations with Atmospheric Emitted Radiance Interferometer (AERI) observations from the ARCS-2 site and Fourier Transform Infrared Radiometric observations from the Ron H. Brown. After completion of the statistical analysis of the comparisons with the infrared data, we plan to publish our results in the open literature.

We also plan to participate in the Water Vapor Intensive Operating Period'2000 to be held at the SGP CART site. The primary issues of interest are calibration of the ARM MWR, comparison with the ETL scanning radiometers, and the evaluation of several calibration targets using LN2 as a coolant. We have recently purchased a very high quality microwave calibration target and will deploy it during the experiment.

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CONFERENCE PROCEEDINGS AND EXTENDED ABSTRACTS

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PROPOSED WORK FOR FY 2001 ACTIVITIES: CONTINUED DEVELOPMENT OF AN INTEGRATED SOUNDING SYSTEM IN SUPPORT OF THE DOE/ARM EXPERIMENTAL PROGRAM (Interagency Agreement No. DE-AI03-94ER61742)

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(1) PARTICIPATION IN WVIOP'2000

ETL proposes to participate in the Water Vapor Intensive Operating Period '2000 to be held at the Southern Great Plains Central Facility and contribute to the data analysis as follows:

- A) Operation of the Circularly Scanning Radiometer: ETL will deploy its CSR that contains radiometers at 20.6 and 31.65 GHz and a temperature profiling radiometer at 60 GHz.
- B) Operation of the University of L'Aquila 5-channel radiometer that has water vapor and temperature channels at 23.6, 31.8, 53.5, 55.5, and 58.0 GHz.
- C) Design and deployment of several calibration targets that have been specially purchased for this experiment. The primary target is a high precision target that was purchased from Zax Millimeter Wave Corporation. The others to be tested are the more conventional ECCOSORB targets. Both ambient and LN2 temperatures will be used in the calibration of ARM MWR and the ETL CSR.
- D) Application of the ETL tipcal diagnostic program to ARM, L'Aquila, and CSR radiometers.

(2) COMPLETION OF THE ANALYSIS OF THE NAURU'99 DATA

- A) ETL will use AERI data from the ARCS2 site as a verification data set for the various types of scaled radiosondes from Nauru'99: i.e., original sondes, Vaisala corrected sondes, and sondes scaled by ARM MWR data. MIRAI MWR data will also be re-analyzed.
- B) Publication of results in the open literature.

(3) COMPLETION OF THE ANALYSIS OF THE NSA/AAO DATA. FROM THE ARCTIC WINTER RADIOMETRIC EXPERIMENT

- A) ETL will use AERI data from the NSA/AAO site as a verification data set for the PWV derived from the NASA and ETL millimeter wave radiometer data taken during the March 1999 experiment.

- B) Analyze both the ETL and the ARM scanning 5-mm radiometer data and to make recommendations for the ultimate disposition of the ARM instrument that was purchased from the Russian firm ATTEX.
- C) Publication of results in the open literature.
- D) Design a millimeter/sub-millimeter radiometer that could complement ARM MWR operation at low temperatures and small water vapor amounts.